

Design, Integration, and Flight Test Results for an Autonomous Surveillance Helicopter



***AHS UAV Specialist Meeting
January 19, 2005***



Dr. M. Takahashi
QSS, Computational Sciences Division
NASA Ames Research Center, CA

G. Schulein
SJS, Army/NASA Rotorcraft Division
NASA Ames Research Center, CA

M. Whalley
Army/NASA Rotorcraft Division
Ames Research Center, CA

J. Howlett
Army/NASA Rotorcraft Division
Ames Research Center, CA

Dr. M. Freed
Computational Sciences Division
NASA Ames Research Center, CA

R. Harris
QSS, Computational Sciences Division
NASA Ames Research Center, CA

Outline

- **Introduction**
- **Airborne Surveillance Planning Problem**
- **Evaluating Surveillance Algorithms**
- **Flight Implementation**
- **Flight Test Results**
- **Concluding Remarks**

Introduction

Autonomous Rotorcraft Project

- NASA (Intelligent Systems) and US Army AFDD



Introduction

Autonomous Rotorcraft Project

- NASA (Intelligent Systems) and US Army AFDD
- Modeling and simulation



Introduction

Autonomous Rotorcraft Project

- NASA (Intelligent Systems) and US Army AFDD
- Modeling and simulation
- Flight control



Introduction

Autonomous Rotorcraft Project

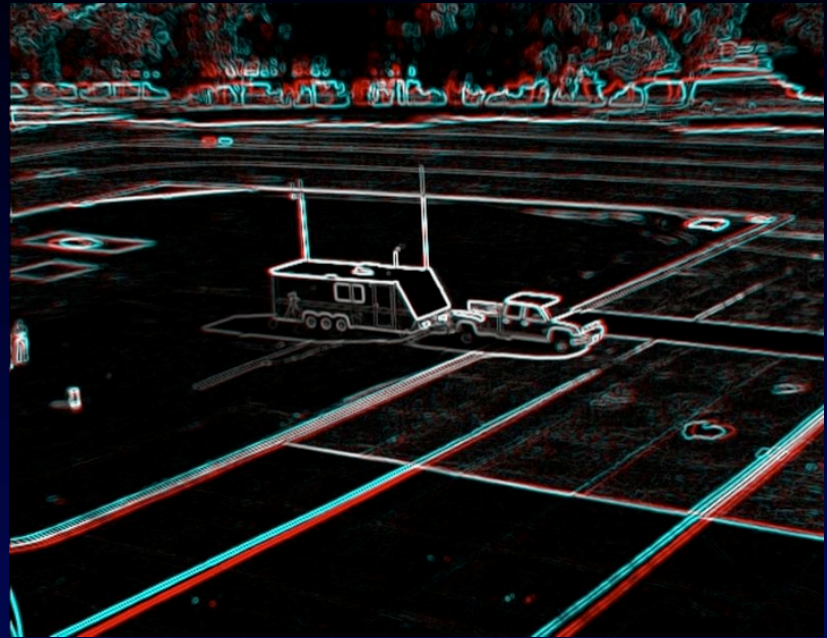
- NASA (Intelligent Systems) and US Army AFDD
- Modeling and simulation
- Flight control
- Route planning for obstacle avoidance



Introduction

Autonomous Rotorcraft Project

- NASA (Intelligent Systems) and US Army AFDD
- Modeling and simulation
- Flight control
- Route planning for obstacle avoidance
- Stereo vision/laser mapping



Introduction

Autonomous Rotorcraft Project

- NASA (Intelligent Systems) and US Army AFDD
- Modeling and simulation
- Flight control
- Route planning for obstacle avoidance
- Stereo vision/laser mapping
- Autonomous landing at non-cooperative sites



Introduction

Autonomous Rotorcraft Project

- NASA (Intelligent Systems) and US Army AFDD
- Modeling and simulation
- Flight control
- Route planning for obstacle avoidance
- Stereo vision/laser mapping
- Autonomous landing at non-cooperative sites
- Contingency planning



Introduction

Autonomous Rotorcraft Project

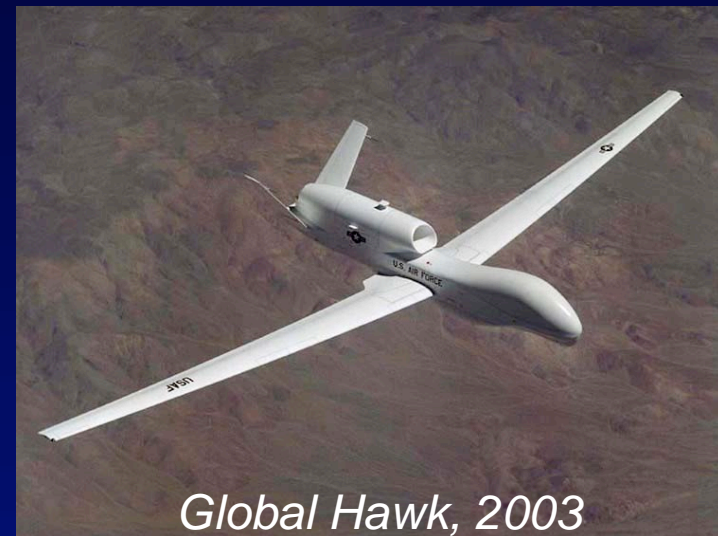
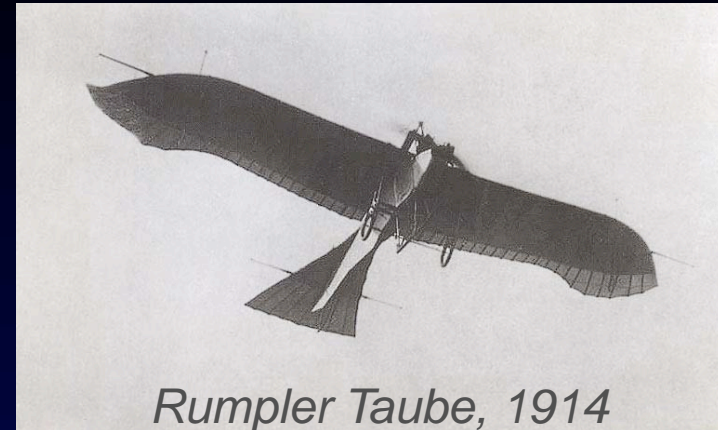
- NASA (Intelligent Systems) and US Army AFDD
- Modeling and simulation
- Flight control
- Route planning for obstacle avoidance
- Stereo vision/laser mapping
- Autonomous landing at non-cooperative sites
- Contingency planning
- **Autonomous surveillance**



Introduction

Surveillance and UAVs

- One of the earliest applications of air vehicles was surveillance
 - Artillery guidance
 - Security
 - Land management
 - Science
- UAVs dramatically increase the availability of surveillance platforms
 - Lower cost
 - More diverse, (possibly) less sophisticated users
- Surveillance is lengthy, repetitive, and largely uneventful making it an ideal candidate for autonomy

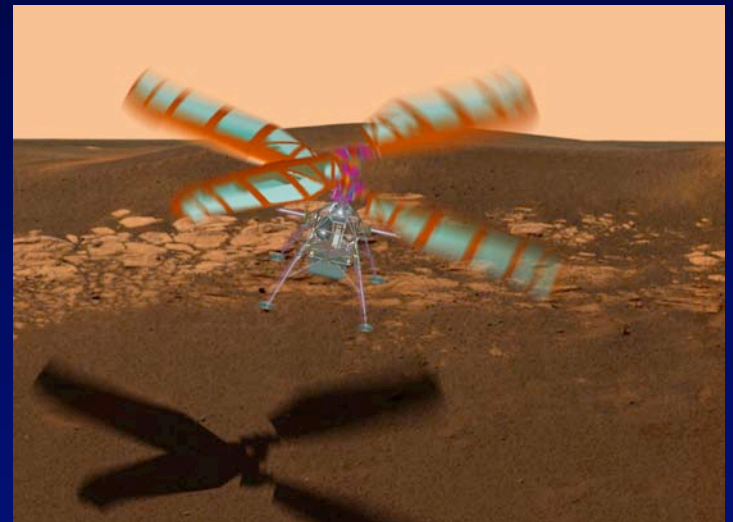


Introduction

Goals

- Develop new autonomous surveillance algorithms
- Implement simulation and flight testbeds for evaluating methods
- Evaluate algorithms/humans to determine which is best for a given situation
- Create a theoretical foundation for surveillance:

Airborne Surveillance Planning Problem



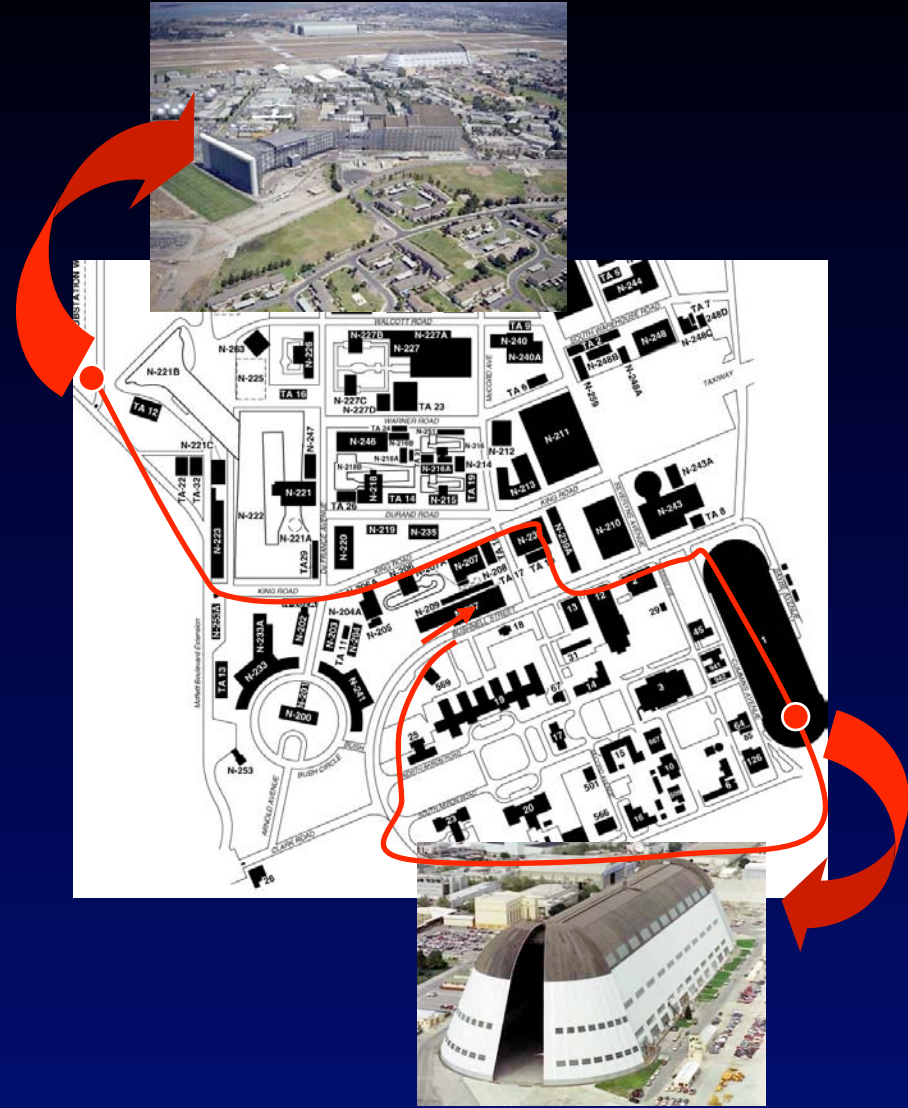
Outline

- Introduction
- **Airborne Surveillance Planning Problem**
- Evaluating Surveillance Algorithms
- Flight Implementation
- Flight Test Results
- Concluding Remarks

Airborne Surveillance Planning Problem

Problem Description

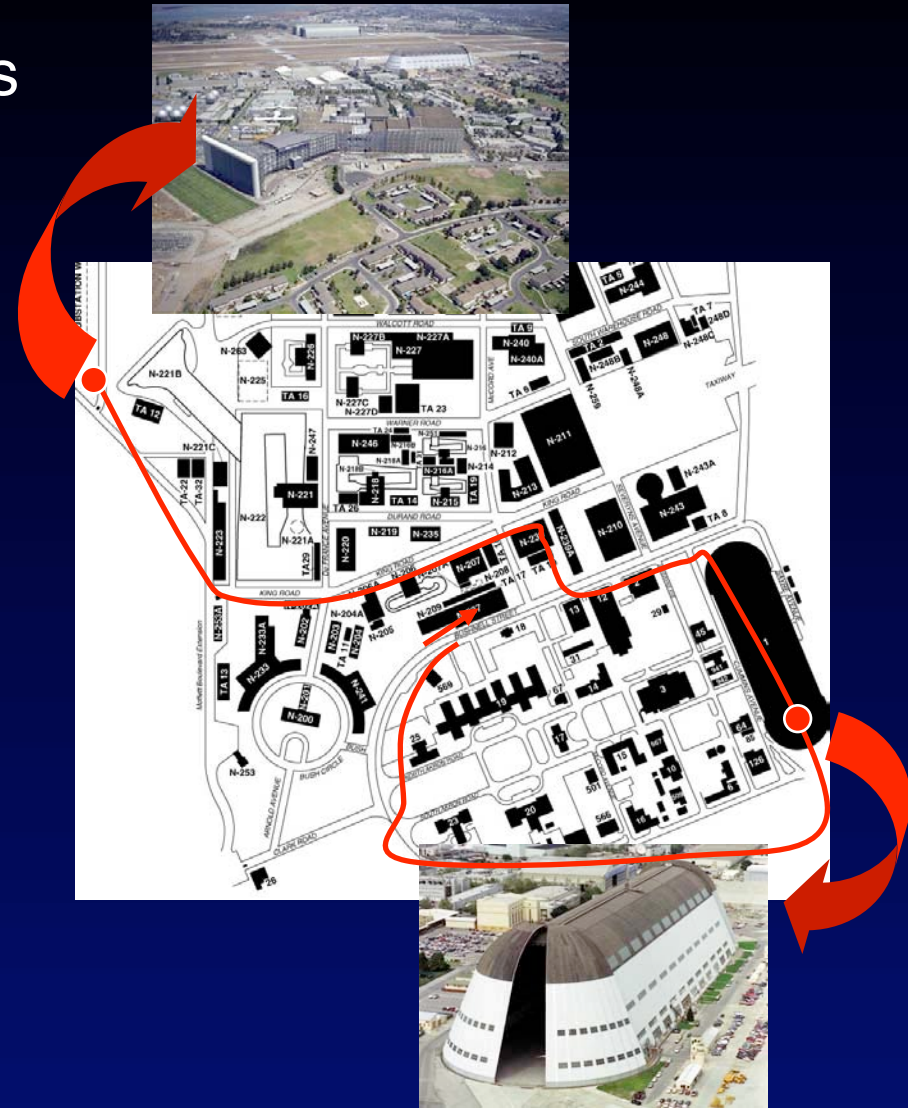
- Repeated or continuous observations to maintain awareness of entity or geographical area
- Need to decide:
 - where to go next
 - what actions to perform



Airborne Surveillance Planning Problem

Problem Description

- Diverse site visit requirements
 - Range of importance/value
 - Some require repeated visits
 - Sites might well be omitted
 - Dynamic targets
- Payload effects
 - Sensor type
 - Lighting conditions
 - Limited pointing capability
- Air vehicle effects
 - Travel time - obstacle avoidance
 - Environmental effects
- Spatial and temporal effects
 - Uniform distribution vs. “clumping”
 - Sites may suddenly be added or removed

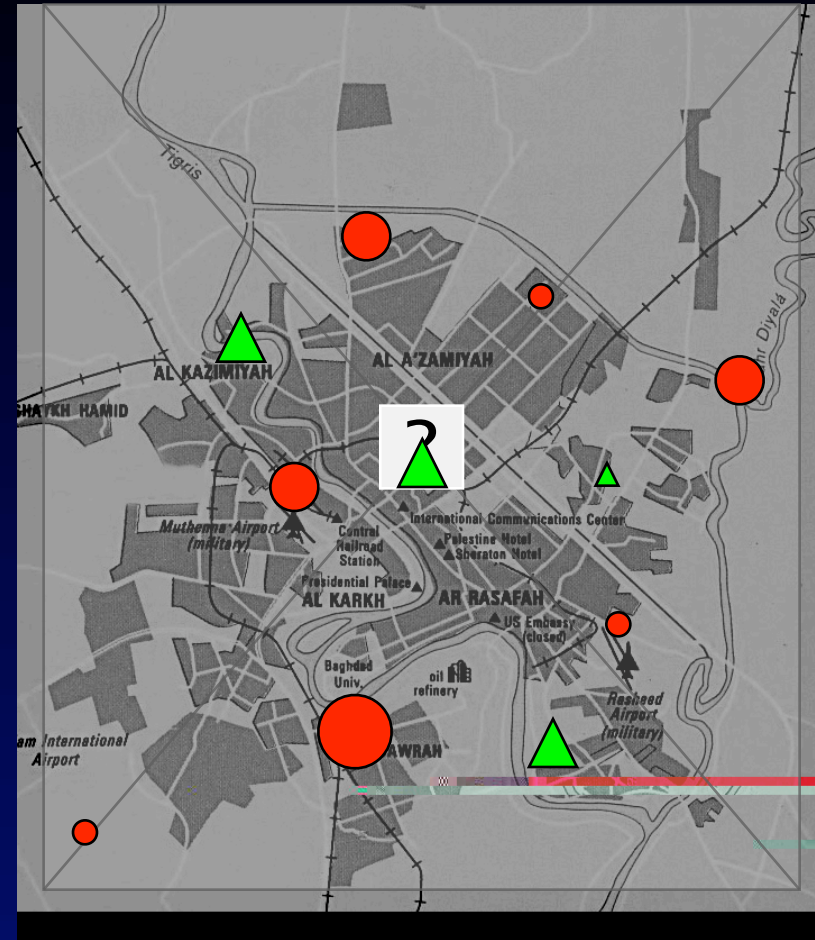


Unlikely that a single algorithm will cover all cases

Airborne Surveillance Planning Problem

A Sample Problem

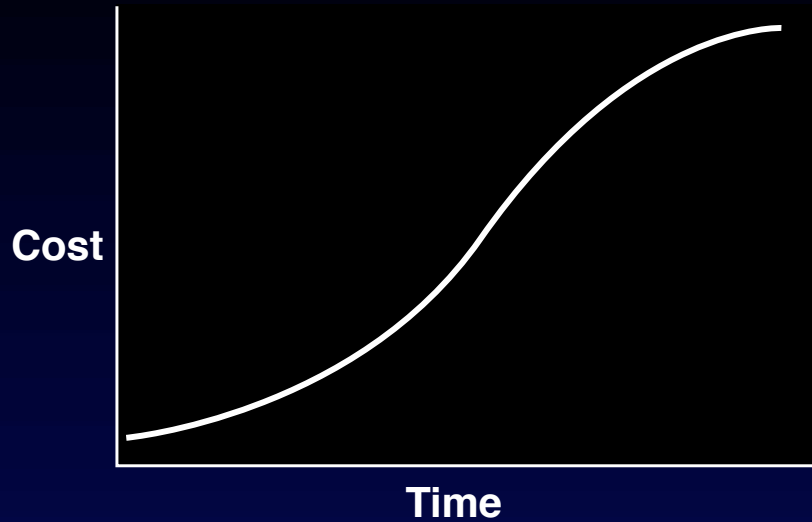
- Valuable Assets
 - perimeter gates
 - warehouses
 - roads
 - airports
- Risk – any asset can start on fire, broken into, etc.
- UAV Goal – do a **good job** detecting events thereby mitigating losses



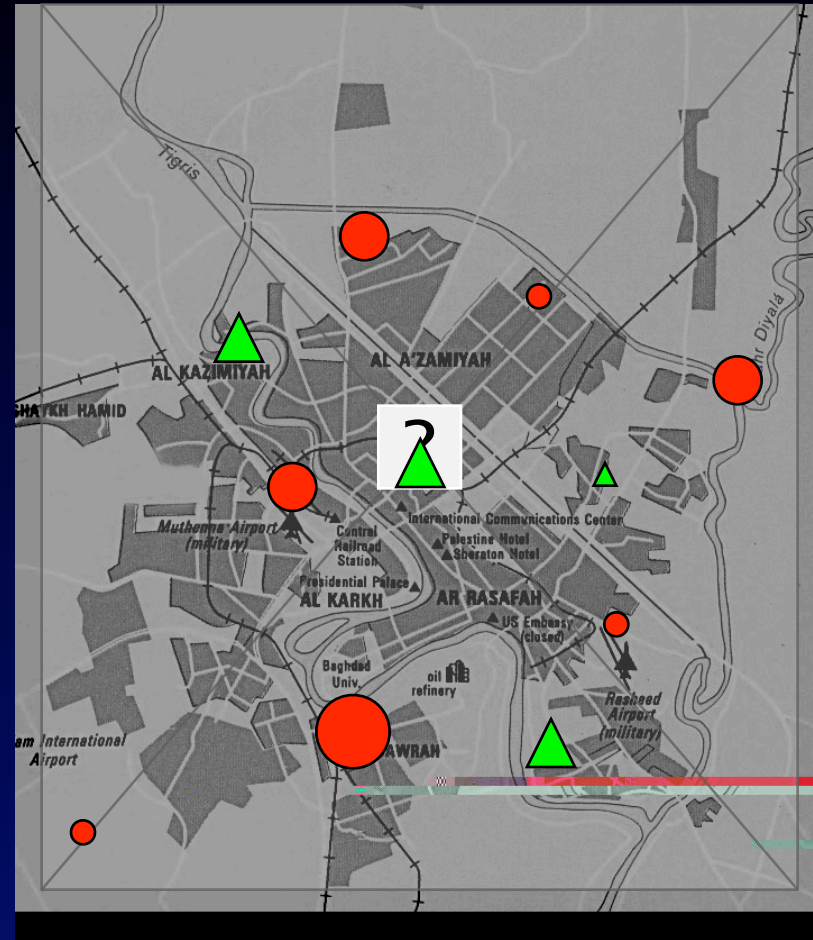
How to quantify “good job”?

Airborne Surveillance Planning Problem

A Decision-Theoretic Approach

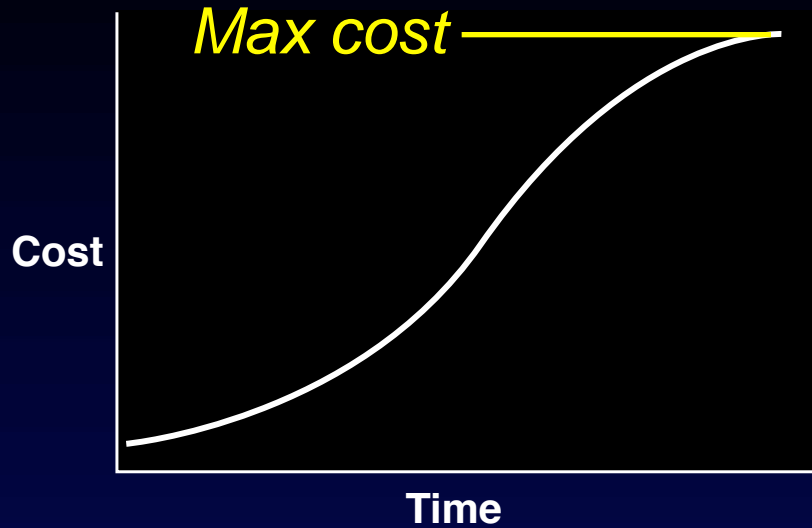


- Each target has an associated cost function (Massios, 2001)

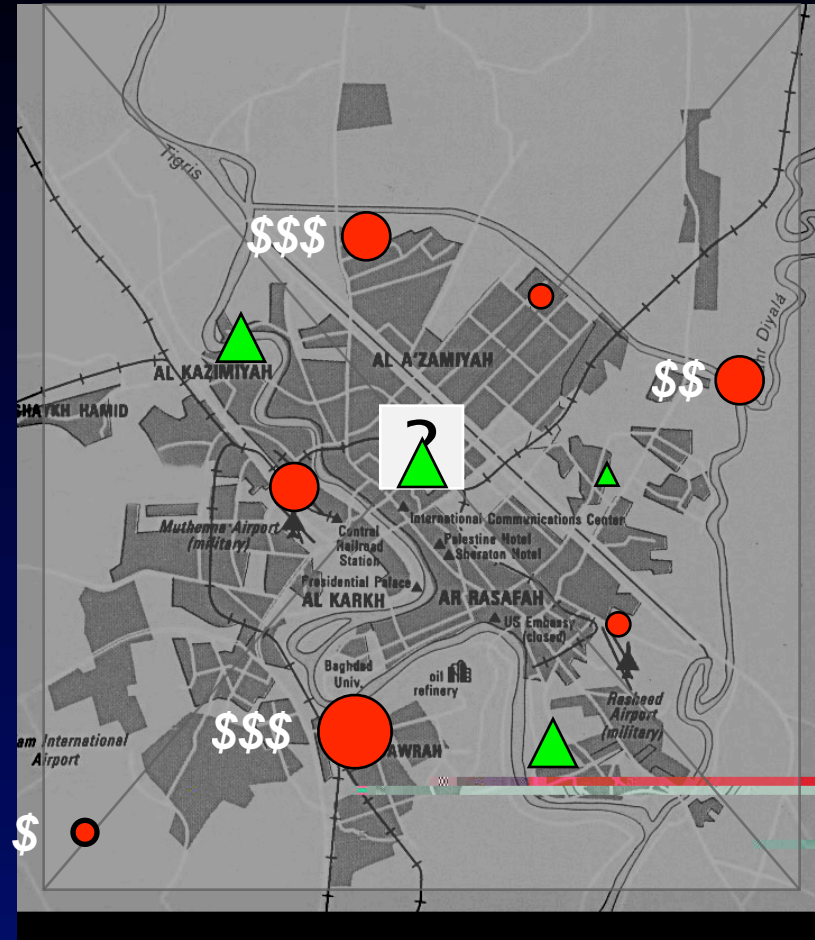


Airborne Surveillance Planning Problem

A Decision-Theoretic Approach

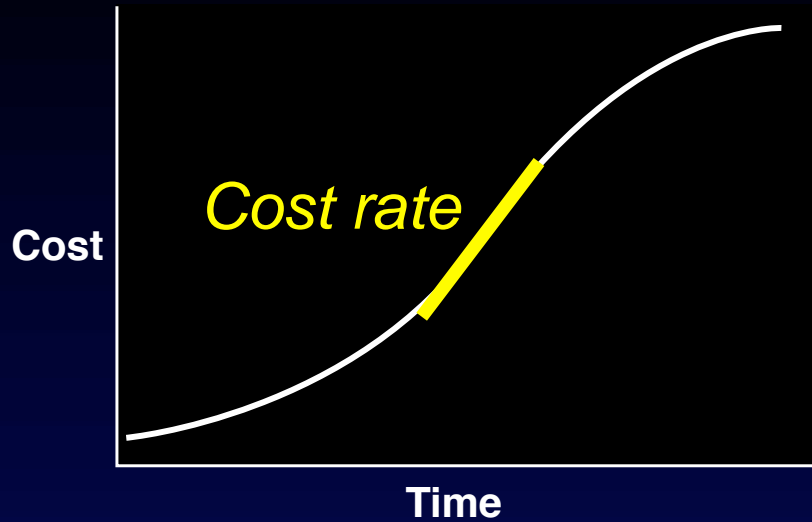


- Each target has an associated cost function (Massios, 2001)
- Some targets are more valuable

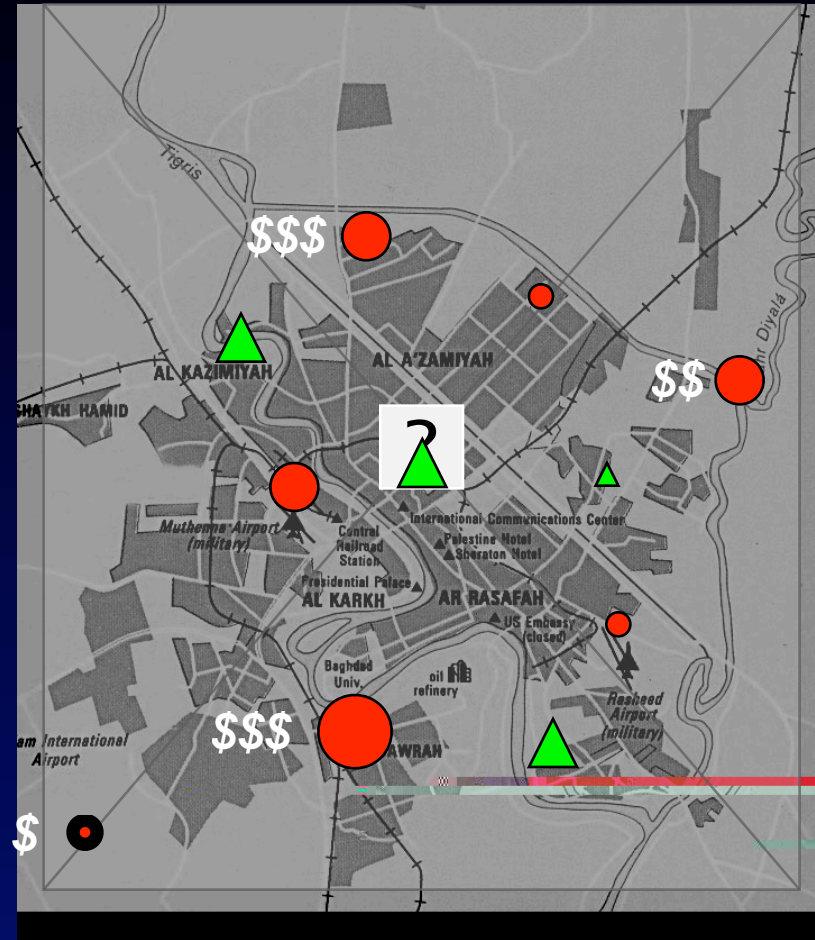


Airborne Surveillance Planning Problem

A Decision-Theoretic Approach

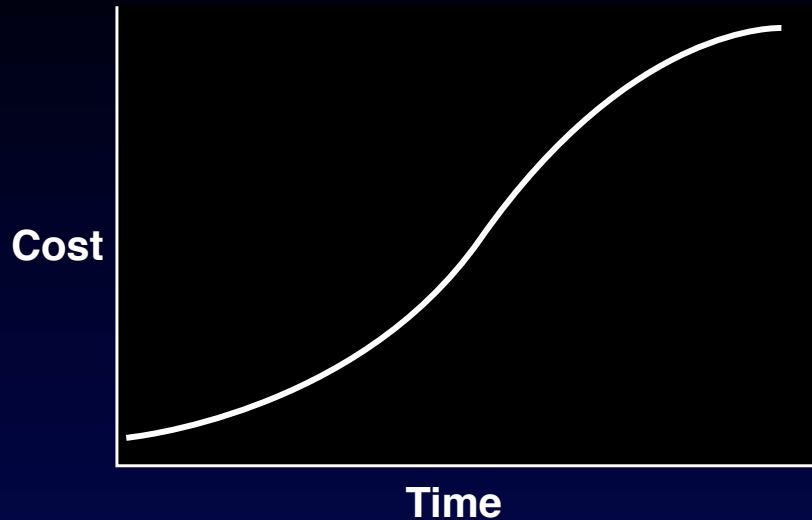


- Each target has an associated cost function (Massios, 2001)
- Some targets are more valuable
- Some targets accrue cost more rapidly

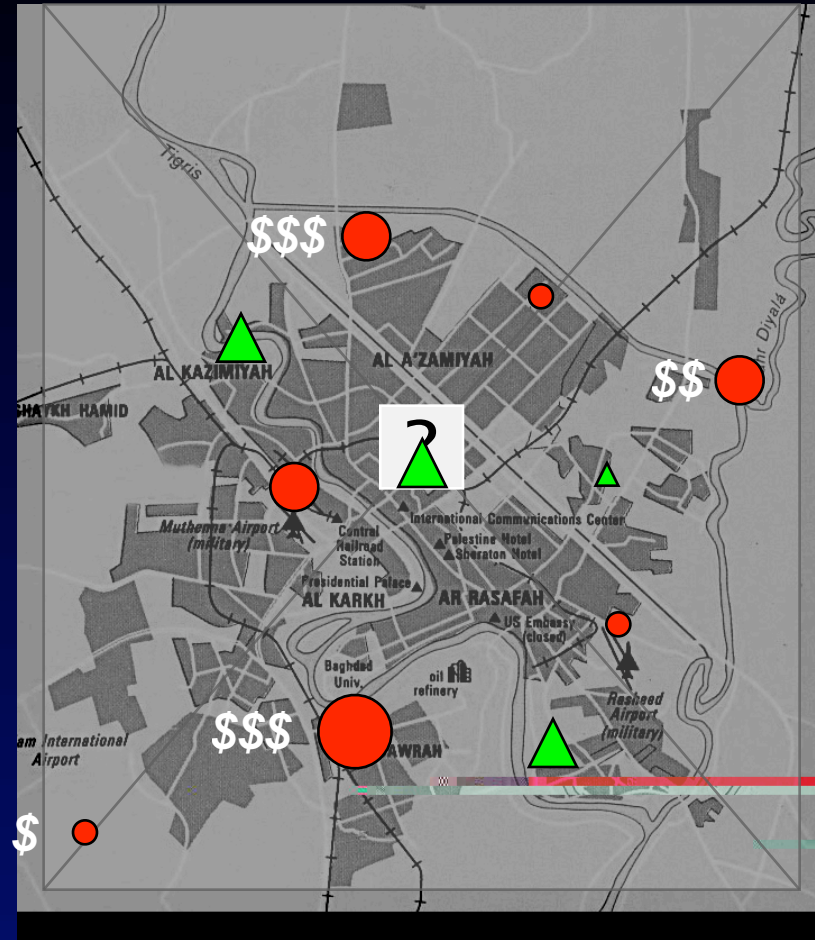


Airborne Surveillance Planning Problem

A Decision-Theoretic Approach



- Each target has an associated cost function (Massios, 2001)
- Some targets are more valuable
- Some targets accrue cost more rapidly
- Probability of occurrence varies with each target



Airborne Surveillance Planning Problem

Expected Cost of Ignorance

$$\text{ECI}_\tau(t_1, t_2) = \int_{t=t_1}^{t_2} p(t) \text{cost}(t_2 - t) dt$$

cost of occurrence function
(e.g. sigmoid)

event probability density function
(e.g., exponential)

- Flight dynamics and travel time integrated into ECI
- Goal is to minimize ECI

Outline

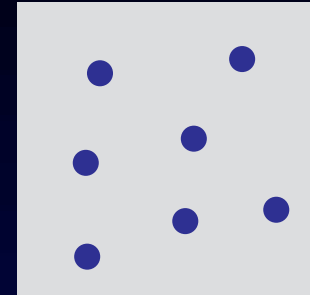
- Introduction
- Airborne Surveillance Planning Problem
- **Evaluating Surveillance Algorithms**
- Flight Implementation
- Flight Test Results
- Concluding Remarks

Evaluating Surveillance Algorithms

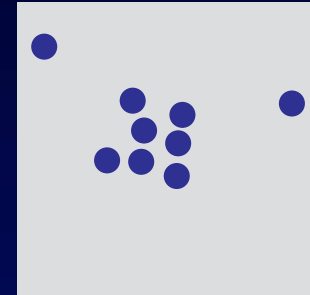
Defining the Problem Space

- Problem space definition
 1. Count
 2. Spatial scale
 3. Spatial distribution
 4. Maximum cost loss
 5. Cost rate
- Characterization permits direct comparison of solution methods

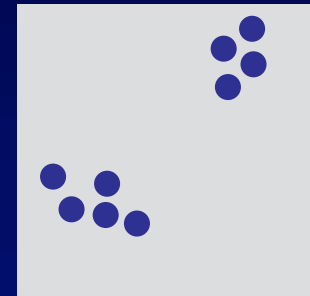
Uniform



Globular



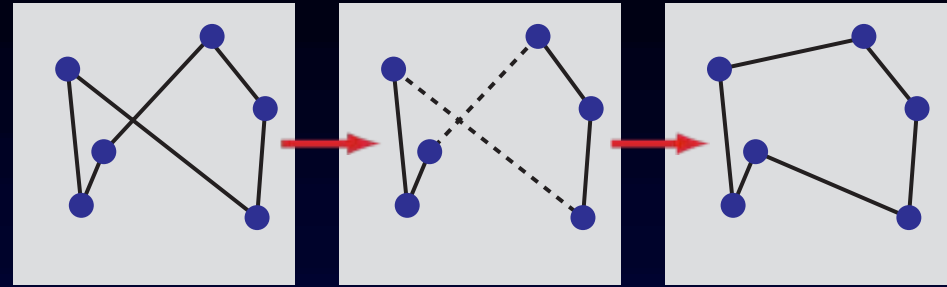
2-Cluster



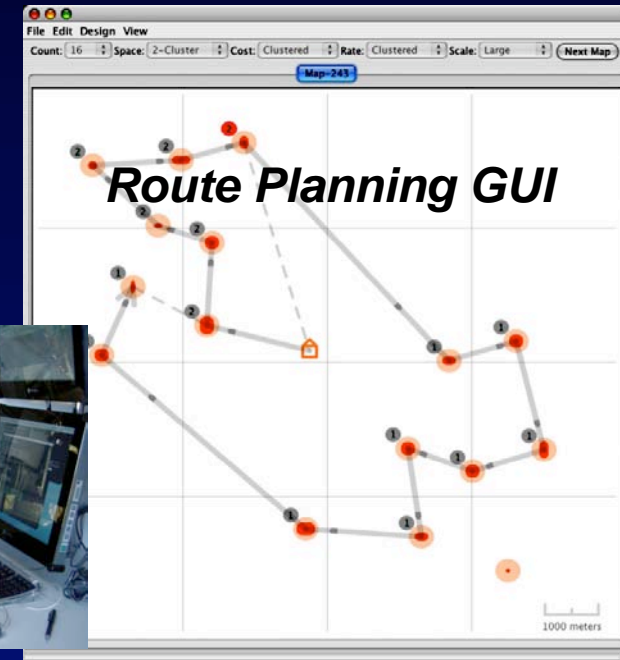
Evaluating Surveillance Algorithms

A Comparative Analysis – 2-Opt versus Human

- GUI symbology indicated max cost, cost rate
- 243 scenarios ~ 6 hours
- Five subjects
- Approximated experienced operators
 - No time limit
 - Training and practice
 - Scoring feedback



2-Opt Solution



Human vs 2-Opt Study

Evaluating Surveillance Algorithms

A Comparative Analysis – 2-Opt versus Human Results

			4			4 Total	8			8 Total	
Scale	Rate	Cost	2-Cluster	Globular	Uniform		2-Cluster	Globular	Uniform		2-Cluster
Large	Clustered	Clustered	-3			-1	2	-1	-8	-3	-5
		Fixed	-3			-1	-2	-2	-4	-3	2
		Uniform	-4		-1	-1	-3	1	-6	-3	-7
	Clustered Total		-3			-1	-1	-1	-6	-3	-3
	Fixed	Clustered	-3			-1	-2		-6	-3	-8
		Fixed	-3			-1	-2	-1	-3	-2	1
		Uniform	-5		-1	-2	-3	1	-5	-2	-7
	Fixed Total		-4			-1	-2		-4	-2	-5
	Uniform	Clustered	-4	-1	1	-1	-3	-2	-9	-5	-5
		Fixed	-4	-1	1	-1	-2	-3	-2	-2	
		Uniform	-5	-3	-2	-3	-3	2	-7	-3	-9
	Uniform Total		-4	-2		-2	-3	-1	-6	-3	-5
Large Total			-4	-1		-2	-2	-1	-6	-3	-4
Clustered							1			1	3

Outline

- Introduction
- Airborne Surveillance Planning Problem
- Evaluating Surveillance Algorithms
- **Flight Implementation**
- Flight Test Results
- Concluding Remarks

Implementation *ARP Yamaha RMAX*

- 184 lb GW, 65 lb payload, one hour endurance
- 3 m rotor diameter



Implementation ARP Yamaha RMAX



- Avionics payload and stub wing

Implementation ARP Yamaha RMAX



- Laser rangefinder(s)

Implementation ARP Yamaha RMAX



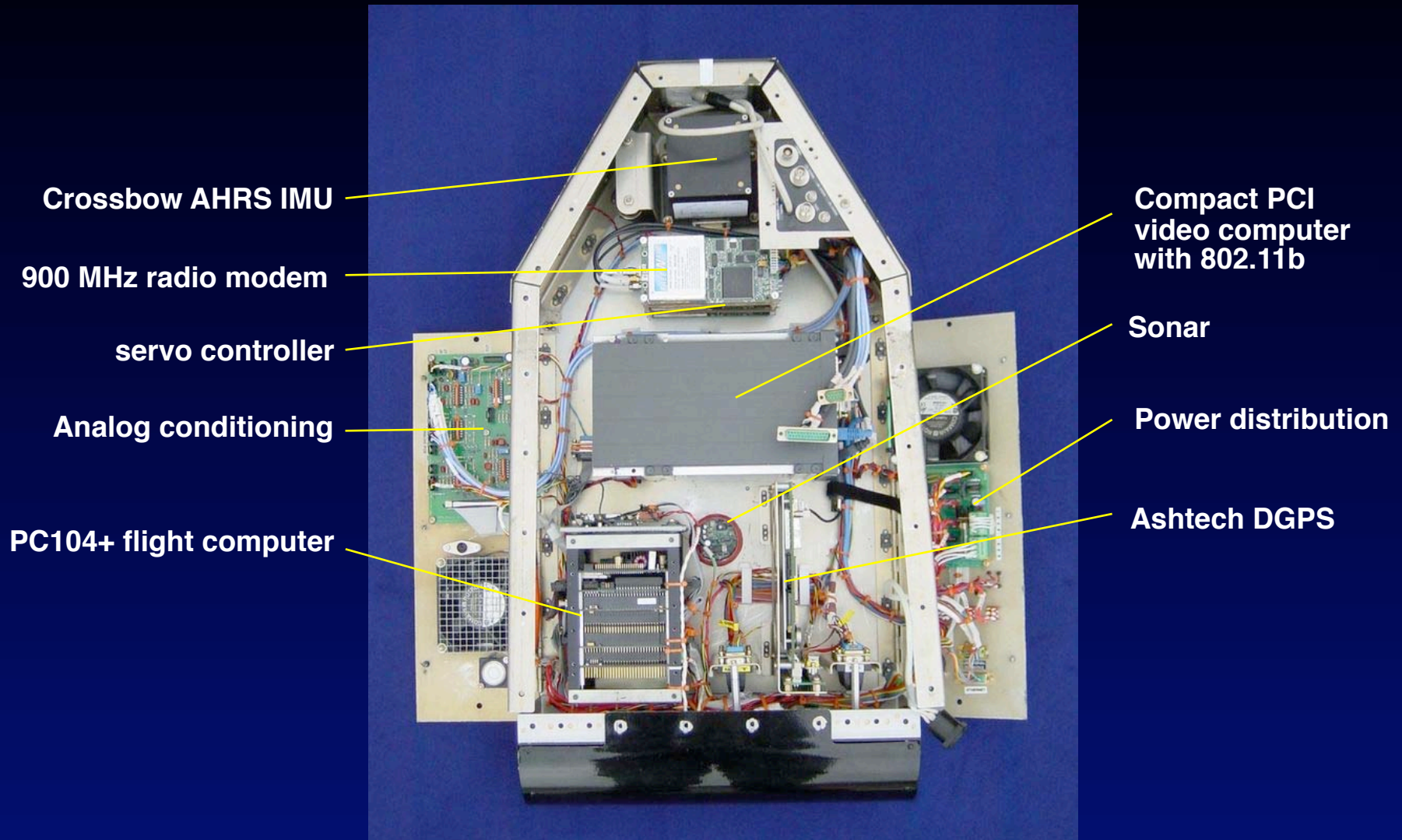
• GPS and telemetry

Implementation ARP Yamaha RMAX

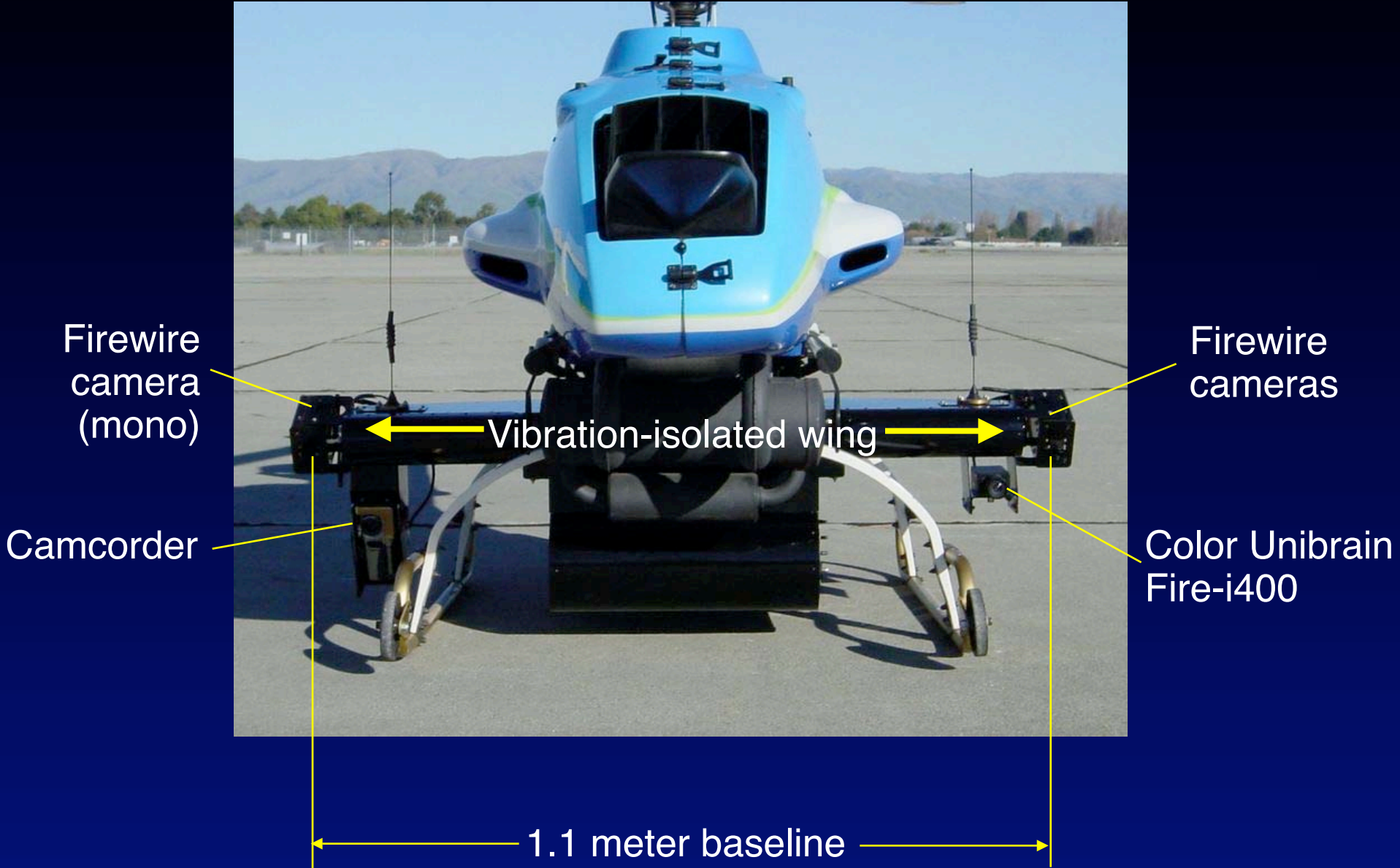


- Weight-on-wheels sensors

Implementation Avionics Payload



Implementation Stub Wing and Cameras



Implementation

Stereo Firewire Cameras

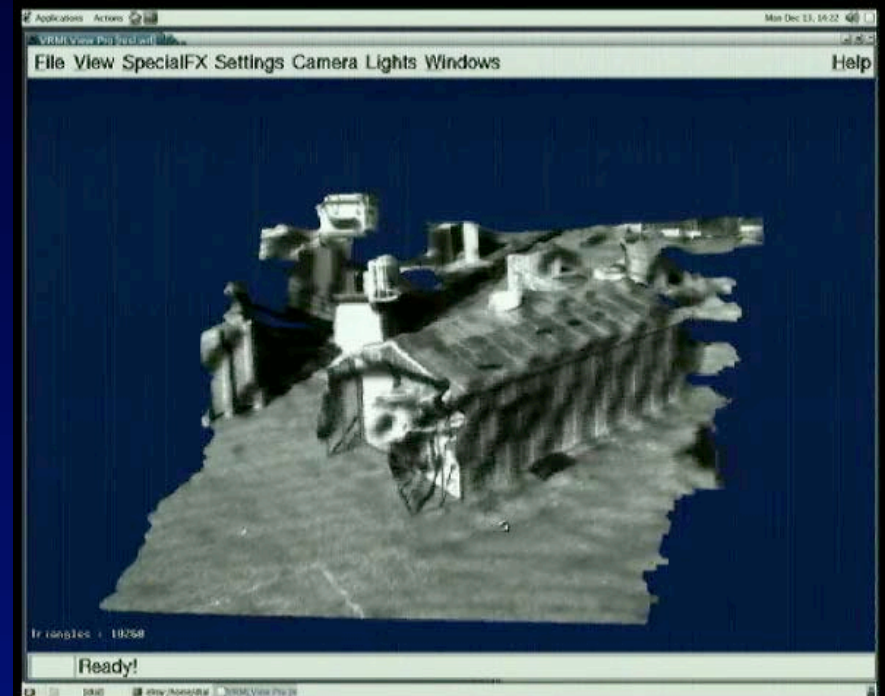


- Point Grey Research - Flea, 45g
- Fixed-focal-length lens, 8 mm, 48g
- Stereo tilt system

Implementation

Passive Obstacle Sensing and Mapping

- Images grabbed from server
- Range map generated using Stereo Pipeline
 - Software implementation gives 160 x 120 disparity map once every 5 seconds
- Real-time transformation to inertial coordinates using 6DOF DGPS/IMU solution and camera tilt
- Wide baseline gives accurate disparity at long distances

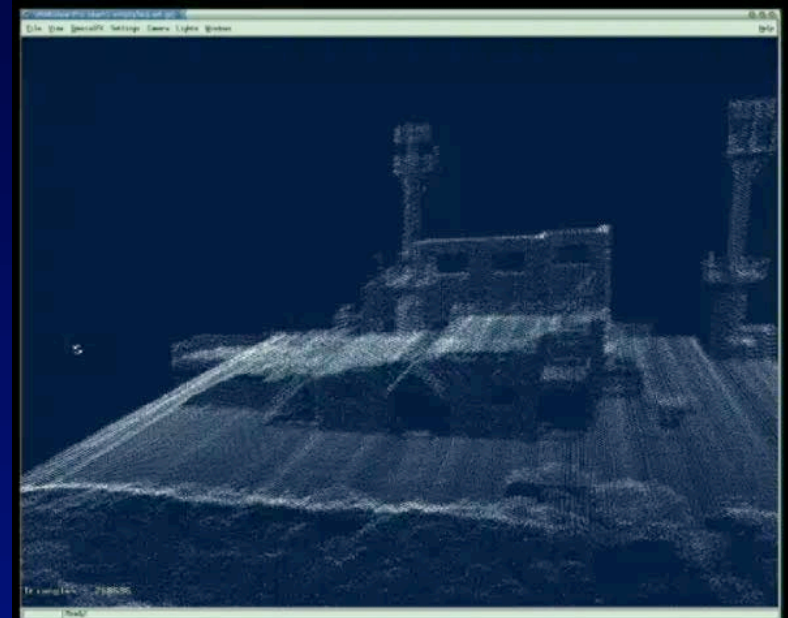


Implementation

Active Obstacle Sensing and Mapping



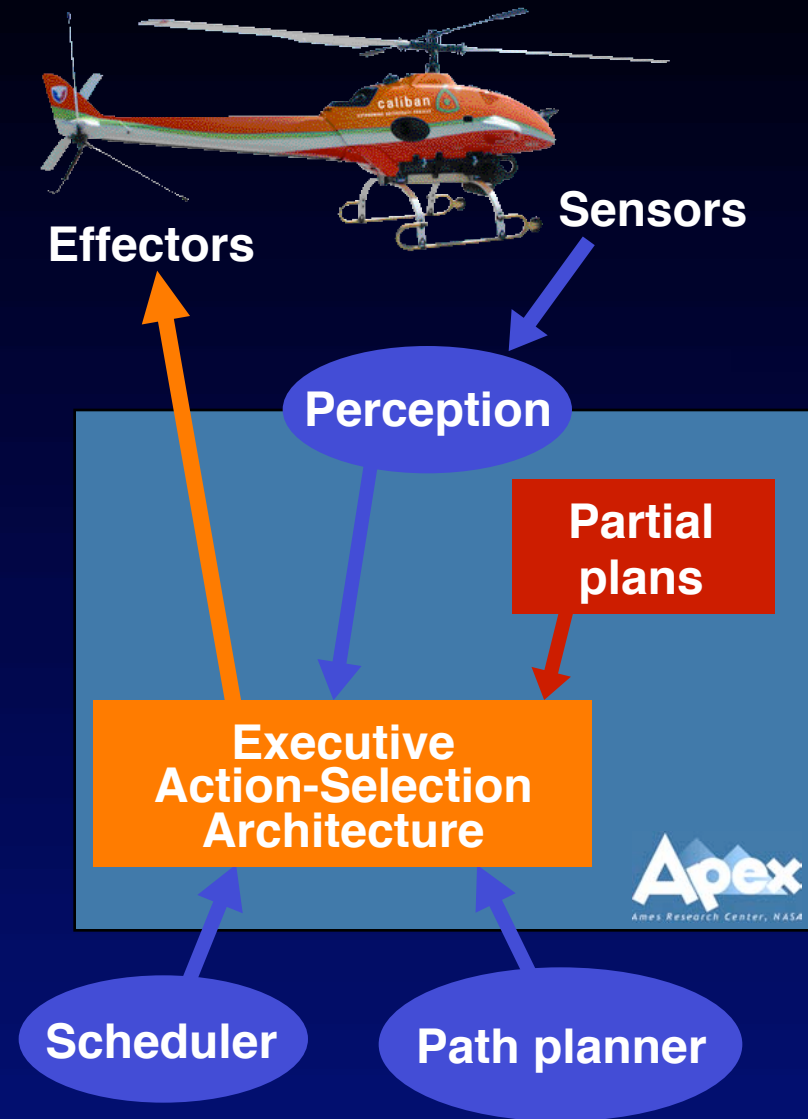
- SICK PLS scanning laser
 - Weight reduced 9.9 lb to 3.6 lb
 - 180 degree field-of-view
 - 13,500 points/sec
 - 1 deg resolution at 75 Hz
 - 0.5 deg resolution at 37.5 Hz
 - 81 m range, 1 cm accuracy
- Reposition-able mount



Implementation

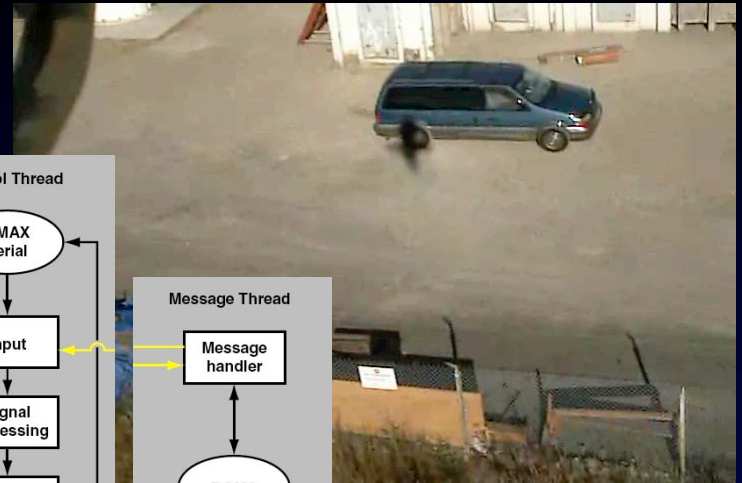
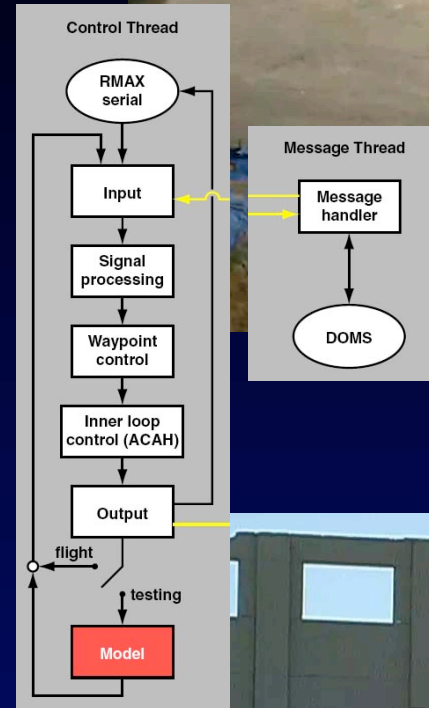
Apex Reactive Planner

- Apex executive architecture constructs solution using library of partial plans (PDL) containing pre-defined contingencies
- Specialists solve subcomponents of the overall plan
- Provides for creation, simulation, and analysis of agent performance (SHERPA)
- Reduces time required for modeling elemental behavior from which complex plans emerge
- Evolving under this project



Implementation Flight Control System

- Model-following control law provides attitude stabilization and waypoint guidance
- Path smoothing
 - Kochanek-Bartels cubic spline fit on-the-fly within pre-defined safe corridor
 - Speed profile to respect pre-defined pitch, bank angle, and climb/descent rate limits
- Control law maintains independent heading control modes



Implementation

Desktop and Hardware-in-the-Loop Simulation

- Identical software load used for hardware-in-the-loop testing
- Integrated math model includes:
 - Validated hover/low speed and forward-flight linear models identified from flight data
 - Actuator dynamic models
 - Sensor quantization and noise
 - Transport delays



Outline

- Introduction
- Airborne Surveillance Planning Problem
- Evaluating Surveillance Algorithms
- Flight Implementation
- **Flight Test Results**
- Concluding Remarks

Flight Test Results

Mission Behavior

- Operator selects targets-of-interest
- Apex computes vantage points
- Apex uses 2-opt to compute sequence
- Obstacle avoidance modifies route as needed
- Targets-of-interest added and deleted



Video

Concluding Remarks

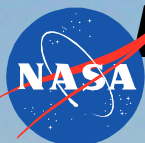
- Surveillance problem defined
- Expected Cost of Ignorance
- Evaluation methodology
- Human versus modified 2-opt
- Flight demonstration
- Robust, flexible autonomous research helicopter platform



Future Work - FY05

- NASA IS – Final demonstration of full surveillance mission
 - Target sequencing
 - Obstacle detection and mapping
 - Route planning
 - Contingency planning for RF and camera failure
- US Army S&T – Landing at non-cooperative site
 - Safe landing area determination
 - GPS-denied





Design, Integration, and Flight Test Results for an Autonomous Surveillance Helicopter



***AHS UAV Specialist Meeting
January 19, 2005***



Dr. M. Takahashi
QSS, Computational Sciences Division
NASA Ames Research Center, CA

G. Schulein
SJS, Army/NASA Rotorcraft Division
NASA Ames Research Center, CA

M. Whalley
Army/NASA Rotorcraft Division
Ames Research Center, CA

J. Howlett
Army/NASA Rotorcraft Division
Ames Research Center, CA

Dr. M. Freed
Computational Sciences Division
NASA Ames Research Center, CA

R. Harris
QSS, Computational Sciences Division
NASA Ames Research Center, CA